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PATENT APPLICATION

MEMBRANE FOR MICRO-ELECTRO-MECHANICAL SWITCH, AND METHODS OF MAKING AND USING IT

TECHNICAL FIELD OF THE INVENTION

This invention relates in general to switches and, more particularly, to micro-electro-mechanical switches having flexible capactive membranes.

BACKGROUND OF THE INVENTION

One existing type of switch is a radio frequency (RF) micro-electro-mechanical switch (MEMS). This existing switch has a substrate with two spaced and conductive posts thereon. A conductive part is provided on the substrate between the posts, and is covered by a layer of a dielectric material. A flexible membrane made of an electrically conductive material extends between the posts, so that a central portion thereof is above the conductive part on the substrate. The portion of the membrane extending between the posts is approximately planar in a non-flexed state. An RF signal is applied to one of the conductive part and the membrane.

In order to actuate the switch, a direct current (DC) bias voltage is applied between the membrane and the conductive part, and produces charges on the membrane and the conductive part which cause them to be electrostatically attracted to each other. This causes the membrane to flex so that a central portion thereof moves downwardly until it contacts the dielectric layer over the conductive part. This is the actuated position of the switch. In this actuated position, the RF signal traveling through one of the membrane and conductive part is capactively coupled substantially in its entirety to the other thereof. In order to deactuate the switch, the DC bias voltage is turned off. The inherent resilience of the membrane then returns the membrane to its original position.

While existing switches of this type have been generally adequate for the their intended purposes, they have not been satisfactory in all respects. One problem is that the DC bias voltage needed to flex the membrane

during actuation can be relatively high, for example from 40 to 100 volts. These high bias voltages tend to introduce charge in the form of electrons into the dielectric layer, and these electrons tend to remain there. The dielectric layer then develops a permanent charge which tends to interact with the membrane so as to keep the membrane in contact with the dielectric layer, even after the bias voltage has been turned off. In other words, the switch latches in its actuated position, and cannot be deactuated. This represents a failure of the switch. Consequently, the buildup of charge in the dielectric layer, due to the use of high bias voltages, reduces the useful operational lifetime of the switch.

A related consideration is that the minimum required bias voltage tends to vary rather significantly with respect to changes in temperature. This is because the substrate and the membrane are made from different materials which have different coefficients of thermal expansion (CTE). Thus, as the ambient temperature is varied from a high temperature to a low temperature, expansion forces are exerted on the membrane at some temperatures, and contraction forces are exerted on it at other temperatures. When expansion forces are being exerted on the membrane, it increases the force needed to flex the membrane and pull it down to the actuated position, which in turn makes it necessary to use a higher bias voltage in order to effect such movement. However, as discussed above, the higher bias voltage tends to reduce the useful lifetime of the device. In order to obtain a meaningful lifetime, existing switches of this type have to be specified for use within a restricted temperature range, which is less than a

desirable range for most commercial applications, and which is much less than the range required for military equipment.

A further consideration with these existing switches is that, although the bias voltage is used to flex the membrane to its actuated position, no external force acts on the membrane when the switch is deactuated. Instead, the inherent resilience of the membrane itself must be sufficient to return the membrane to its original position. As discussed above, charge buildup in the dielectric layer can tend to electrostatically attract the membrane, and thus resist movement of the membrane back to its deactuated position. One way to address this problem is to increase the resilient restoring force within the membrane itself, but a drawback is that a larger force is needed to flex the membrane to its actuated position, which in turn means that a higher bias voltage is needed for actuation of the switch. However, as discussed above, higher bias voltages increase the rate at which residual charge builds up within the dielectric layer, which in turn reduces the useful lifetime of the switch.

Still another consideration is that existing switches have relatively thin membranes, in order to give the membrane sufficient flexibility to move to its actuated position in response to the bias voltage. However, the relatively small cross-sectional area of these existing membranes results in a membrane resistance of approximately 0.5 ohms to 1.0 ohms, which is higher than ideally desirable, and which limits the amount of current that can reasonably flow through the membrane,

thus limiting the amount of power which the switch can handle.

A further consideration which limits the power handling capability of these existing switches is that a large RF current can produce a magnetic field which tends to keep the membrane in the actuated position, even after the DC bias voltage has been turned off. As noted above, it is possible to increase the resilient restoring force which urges the membrane upwardly, but this in turn creates the need to increase the bias voltage that actuates the switch, and decrease the higher bias voltage has the undesirable effect of reducing the operational lifetime of the switch.

SUMMARY OF THE INVENTION

From the foregoing, it may be appreciated that a need has arisen for a method and apparatus for making and operating a switch of the type having a flexible membrane, so that the switch can be reliably operated across a wide temperature range with a significantly lower pull-in voltage than existing switches. According to one form of the present invention, a method and apparatus are provided to address this need, and utilize a switch which includes a base section, an electrically conductive part supported on the base section, and a membrane having first and second ends supported at spaced locations on the base section, the membrane having an electrically conductive portion disposed between the ends thereof. The method and apparatus involve: providing between the first and second ends of the membrane resilient structure which is capable of yieldably expanding in a direction lengthwise of the membrane so as to increase an effective length of the membrane; and responding to an applied voltage between the conductive part and the conductive portion by resiliently flexing the membrane so that the membrane moves from a first position where the membrane is unflexed and the conductive portion is spaced from the conductive part to a second position where the membrane is flexed and the conductive portion is adjacent the conductive part, the resilient structure expanding as the membrane is moved from the first position to the second position

A different form of the present invention relates to fabrication of a switch, and involves: forming an electrically conductive part on a base section; forming over the conductive part a spacer layer having a top

surface with a portion that defines one of a groove and a ridge with respect to a remainder of the top surface; forming over the top surface a membrane layer which has first and second ends engaging spaced portions of the base section disposed on opposite sides of the conductive part, and which has an electrically conductive portion between the first and second ends; and removing the spacer layer so as to leave the membrane layer supported by the ends thereof with the electrically conductive portion spaced above the conductive part.

BRIEF DESCRIPTION OF THE DRAWINGS

A better understanding of the present invention will be realized from the detailed description which follows, taken in conjunction with the accompanying drawings, in which:

FIGURE 1 is diagrammatic fragmentary sectional side view of an apparatus which includes a micro-electro-mechanical switch embodying the present invention;

FIGURE 2 is a diagrammatic fragmentary top view of the apparatus of FIGURE 1, and also diagrammatically shows a control circuit which effects operation of the switch;

FIGURE 3 is a diagrammatic fragmentary sectional side view similar to FIGURE 1, but showing a different operational position of a membrane of the switch;

FIGURE 4 is a diagrammatic fragmentary sectional side view similar to FIGUREs 1 and 3, but showing still another operational position of the membrane of the switch;

FIGURE 5 is a diagrammatic fragmentary sectional side view of the switch of FIGURE 1 at a point in time during a process of fabricating the switch;

FIGURE 6 is a diagrammatic fragmentary sectional side view similar to FIGURE 1 but showing a different apparatus which includes a switch embodying the present invention, and which is an alternative embodiment of the apparatus of FIGURE 1;

FIGURE 7 is a diagrammatic fragmentary sectional side view showing the apparatus of FIGURE 6 at a point in time during the fabrication of the switch;

FIGURE 8 is a diagrammatic fragmentary sectional side view similar to FIGURE 6 but showing yet another

apparatus which includes a switch embodying the invention, and which is an alternative embodiment of the apparatus of FIGURE 6;

FIGURE 9 is a diagram showing several different types of membranes used in micro-electro-mechanical switches, including membranes from switches which embody the present invention;

FIGUREs 10-17 are graphs which diagrammatically show various different characteristics of one or more of the membranes shown in FIGURE 9; and

FIGUREs 18 and 19 are each a diagrammatic side view of a portion of one of the membranes of FIGURE 9, showing how that membrane will respond to variations in temperature.

DETAILED DESCRIPTION OF THE INVENTION

FIGURE 1 is a diagrammatic fragmentary sectional side view of an apparatus which includes a micro-electro-mechanical switch (MEMS) 10 that embodies the present invention. FIGURE 2 is a diagrammatic fragmentary top view of the apparatus of FIGURE 1, showing the switch 10.

The switch 10 includes a silicon semiconductor substrate 13 having on an upper side thereof an oxide layer 14, which in the illustrated embodiment is silicon dioxide. Although the substrate 13 is a silicon semiconductor material in the disclosed embodiment, it could alternatively be some other suitable material, such as gallium arsenide (GaAs), or a suitable alumina. As shown in FIGURE 1, two posts 17 and 18 are provided at spaced locations on the oxide layer 14, and are each made of a conductive material such as gold. The substrate 13, the oxide layer 14 and the posts 17 and 18 can be referred to as a base section of the switch 10.

An electrically conductive electrode 22 is provided on the upper surface of the oxide layer 14, intermediate the posts 17 and 18. As seen in FIGURE 2, the electrode 22 is an elongate strip. The electrode 22 serves as a transmission line. The portion of the electrode 22 located between the posts 17 and 18 is covered by a dielectric layer 23, which is made of silicon nitride.

A conductive membrane 31 extends between the upper ends of the posts 17 and 18. The membrane 31 is made of an aluminum alloy which is known in the art, and which contains approximately 99% aluminum by weight, with most or all of the remainder being silicon and titanium. However, other suitable materials could alternatively be used for the membrane 31. The membrane 31 has ends 32

and 33, which are each fixedly supported on the top portion of a respective one of the posts 17 and 18. The membrane 31 has intermediate the ends 32 and 33 a central portion 36, which is disposed directly above the electrode 22 and the dielectric layer 23. Membrane 31 has adjacent its ends 32 and 33 respective outer portions 37 and 38. The central portion 36 and the outer portions 37 and 38 are approximately co-planar.

The membrane 31 has an expansion section 41 between the central portion 31 and the outer portion 37, and has a similar expansion section 42 between the central portion 36 and the outer portion 38. The expansion sections 41 and 42 are each approximately U-shaped. In particular, the expansion section 41 includes spaced vertical portions 46 and 47, and a horizontal portion 48 that extends between the lower ends of the vertical portions 46 and 47. In the operational position shown in FIGURE 1, the horizontal portion 48 is approximately parallel to the central portion 36 and the outer portion 37, and the vertical portions 46 and 47 are each approximately perpendicular to the horizontal portion 48, the central portion 46 and the outer portion 37. The expansion section 42 is similar, and includes vertical portions 51 and 52, and a horizontal portion 53.

The portions 48 and 53 have the same length, and the portions 46-47 and 51-52 all have the same height. The outer portions 37 and 38 have the same length. In FIGURE 1 the portions 37 and 38 each have the same length as the portions 48 and 53.

In operation, a radio frequency (RF) signal with a frequency in the range of approximately 300 MHz to 90 GHz will be traveling through one of the membrane 31 or the

electrode 22 that serves as a transmission line. More specifically, the RF signal may be traveling from the post 17 through the membrane 31 to the post 18. Alternatively, with reference to FIGURE 2, the RF signal may be traveling through the electrode 22 from the lower portion of the figure toward upper portion of the figure. Actuation of the switch 10 is carried out under control of a direct current (DC) bias voltage, which is applied between the membrane 31 and the electrode 22 by a control circuit which is of a known type, and which is indicated diagrammatically at 61 in FIGURE 2 by broken lines. This bias voltage is also referred to as a pull-in voltage (V_p).

When the bias voltage is not applied to the switch 10, the membrane 31 has the position which is shown in FIGURE 1. As discussed above, an RF signal is passing through one of the membrane 31 and the electrode 22. For purposes of convenience in the discussion which follows, it will be assumed that this RF signal is passing through the electrode 22. When the membrane 31 is in the position of FIGURE 1, the RF signal traveling through the electrode 22 will pass through the switch 10 and then continue traveling through the electrode 22, with no significant coupling of this RF signal from the electrode 22 over to the membrane 31.

In order to actuate the switch 10, a DC bias voltage is applied by the control circuit 61 between the electrode 22 and the membrane 31. This voltage produces charges on the membrane 31 and on the electrode 22, which cause the central portion 36 of the membrane 31 to be urged toward the electrode 22 by an electrostatic force. This attractive force causes the membrane 31 to flex

downwardly, so that its central portion 36 moves toward the electrode 22. As this occurs, the vertical portions 46 and 47 of the expansion section 41 will each tilt slightly in relation to the horizontal portion 48, so that their upper ends move away from each other. The vertical portions 51 and 52 of the expansion section 42 will experience a similar tilting movement. This results in a slight increase in the effective length of each of the expansion sections 41 and 42, which in turn results in a slight increase in the overall effective length of the membrane 31. The membrane 31 can thus move downwardly more easily than would be the case if the membrane 31 did not have the expansion sections 41 and 42.

As the membrane 31 flexes downwardly, it reaches the position shown in FIGURE 3, where at least part of each horizontal section 48 and 53 engages the oxide layer 41. In this position, the central portion 36 of the membrane 31 will still be spaced a small distance above the dielectric layer 23 that covers the electrode 22. Further downward movement of the central portion 36 of the membrane 31 requires flexing of the central portion 36 itself. This additional flexing requires a higher attractive force between the central portion 36 and the electrode 22 than was needed to effect initial downward movement of the central portion 36. On the other hand, since the central portion 36 and the electrode 22 are now physically closer than they were in the operational position shown in FIGURE 1, the electrostatic attraction between them will be inherently higher than it was in the operational position of FIGURE 1. Thus, the additional force needed to effect further downward movement of the

central portion 36 from the operational position of FIGURE 3 to the operational position of FIGURE 4 will occur without any need to increase the DC bias voltage that is being applied between the membrane 31 and the electrode 22.

More specifically, from the position shown in FIGURE 3, the central portion 36 of the membrane flexes until its center engages the top of the dielectric layer 23, as shown in FIGURE 4. This is the actuated position of the switch 10. In this position, the capacitive coupling between the electrode 22 and the central portion of the membrane 36 is approximately 100 times greater than when the membrane is in the deactuated position shown in FIGURE 1. Consequently, the RF signal which is traveling through the electrode 22 will be coupled substantially in its entirety from the electrode 22 over into the membrane 31, and will tend to have components which travel away from the central portion 36 in opposite directions, toward each of the posts 17 and 18. Alternatively, if the RF signal had been traveling through the membrane 31 from the post 17 to the post 18, the RF signal would have been coupled substantially in its entirety from the central portion 36 to the electrode 22, and would tend to travel away from the switch 10 in each of opposite directions through the electrode 22.

Once the membrane 31 has reached the actuated position shown in FIGURE 4, the control circuit 61 may optionally reduce the DC bias voltage to a standby or hold value, which is less than the pull-in voltage needed to initiate downward movement of the membrane 31 from the position of FIGURE 1, but which is sufficient to maintain

the membrane 31 in the actuated position of FIGURE 4 once it has reached this actuated position.

In order to deactivate the switch 10, the control circuit 61 turns off the DC bias voltage which is being applied between the membrane 31 and the electrode 22. The resilience of the flexed central portion 36, in association with engagement of the adjacent expansion sections 41 and 42 with the oxide layer 14, results in a relatively strong restoring force, which initiates upward movement of the central portion 36 away from the dielectric layer 23 and the conductive part 22. Once upward movement is initiated, the membrane 31 will continue moving, and will move through the position of FIGURE 3 as it returns to the position of FIGURE 1 due to resilience within the membrane 31. In this regard, the expansion sections 41 and 42 each resiliently contract to their original shape and length.

FIGURE 5 is a diagrammatic fragmentary sectional side view of the switch 10 of FIGURE 1, showing a point in time during fabrication of the switch 10 according to a process which embodies the present invention. In more detail, fabrication begins with the silicon substrate 13, and then the oxide layer 14 is formed through deposition of silicon dioxide on the substrate 13. Then, the electrode 22 is formed on the oxide layer 14, for example by depositing a layer of gold and then carrying out a patterned etch.

Next, the dielectric layer 23 is formed, by depositing a layer of silicon nitride, and then carrying out a patterned etch. A spacer 76 is then formed over the oxide layer 14 and the dielectric layer 23. The spacer 76 is a photoresist material of a type known to

those skilled in the art. The photoresist layer is then patterned and etched one or more times, in order to define spaced, transverse grooves 77 and 78 in a top surface of the spacer 76, and so as to define vertical side surfaces 81 and 82 adjacent the locations where the posts 17 and 18 will be formed. The grooves 77 and 78 each have an approximately rectangular cross section.

Next, the posts 17 and 18 are formed, by depositing a layer of gold and then carrying out a patterned etch to remove unwanted material, so as to leave just the posts 17-18. Next, a layer of the above-mentioned aluminum alloy is deposited over the spacer 76, the electrodes 17-18 and the oxide layer 14, and is then patterned and etched to form the membrane 31. At this point, the structure has the configuration shown in FIGURE 5.

Next, an etch procedure referred to as a membrane release etch is carried out in order to remove the spacer 76 in its entirety. The membrane release etch may, for example, be a plasma etch of a known type, or any other suitable etch which will attack the material of the photoresist that forms the spacer 76. This etch leaves the membrane 31 suspended on the posts 17-18 by its ends 32 and 33. This is the finished configuration of the switch 10, which is shown in FIGURE 1.

FIGURE 6 is a diagrammatic fragmentary sectional side view similar to FIGURE 1, but showing a switch 110 which is alternative embodiment of the switch 10 of FIGURE 1. In this regard, the switch 110 is generally similar to the switch 10 of FIGURE 1, except that the switch 110 has a membrane 131 which is different from the membrane 31 of the switch 10. Other structure within

FIGURE 6 is identified by the same reference numerals used in FIGURE 1.

The membrane 131 of FIGURE 6 is made from the same material as the membrane 31 of FIGURE 1. It includes ends 132 and 133 which are each fixedly supported on a respective one of the posts 17 and 18. The membrane 131 has a central portion 136, and two outer portions 137 and 138 that are each adjacent a respective one of the ends 132-133. The membrane 31 has a substantially U-shaped expansion section 141 between the central portion 136 and the outer portion 137, and a further substantially U-shaped expansion section 142 between the central portion 136 and the outer portion 138. The central portion 136 and the outer portions 137 and 138 are approximately co-planar with each other when the membrane 131 is not flexed. One difference between the membrane 131 of FIGURE 6 and the membrane 31 of FIGURE 1 is that the expansion sections 41 and 42 of the membrane 31 project downwardly with respect to the central portion 36 thereof, whereas the expansion sections 141 and 142 of the membrane 131 project upwardly with respect to the central portion 136 thereof.

More specifically, the expansion section 141 includes two spaced vertical portions 146 and 147 which are each perpendicular to and extend upwardly from a respective one of the central portion 136 and the outer portion 137. The expansion section 141 further includes a horizontal portion 148 which is perpendicular to and extends between the upper ends of the vertical portions 146 and 147. Similarly, the expansion section 142 includes vertical portions 151 and 152 which each extend perpendicular to and upwardly from an end of a respective

one of the central portion 136 and the outer portion 138, and includes a horizontal portion 153 which is perpendicular to and extends between the upper ends of the vertical portions 151-152.

The operation of the switch 110 of FIGURE 6 is generally similar to the operation of the switch 10 of FIGURE 1, except as discussed below. More specifically, as the membrane 131 flexes downwardly during actuation of the switch 110, it should be evident that the expansion sections 141 and 142 will not engage the oxide layer 14. Thus, the membrane 131 will simply carry out a generally progressive flexing movement from the position shown in FIGURE 6 to a position in which the middle of the central portion 136 is engaging the top of the dielectric layer 23. Also, when the DC bias voltage supplied to the switch 110 is terminated, in order to deactuate the switch, the restoring force which initiates upward movement of the membrane 131 back to the position shown in FIGURE 6 is effected by inherent resilience throughout the portion of the membrane 131 located between the electrodes 17-18.

FIGURE 7 is a diagrammatic fragmentary sectional side view of the switch 110, showing a point in time during fabrication of the switch 110 according to a process which embodies the present invention. In this regard, the substrate 13, the oxide layer 14, the electrode 22 and the dielectric layer 23 are all formed in a manner similar to that described above in association with FIGURE 5. Then, a spacer layer 176 is formed from a known photoresist or polyimide material, and is patterned and etched to an appropriate shape, including formation of side surfaces 181-182. Then, a

further layer of the same or an equivalent material is deposited on the spacer 176, and is patterned and etched to form spaced and parallel ridges or spacers 177 and 178.

Then, the membrane 131 is fabricated in a manner similar to that explained above with respect to formation of the membrane 31 shown in FIGURE 5. This results in the structure shown in FIGURE 7. Then, a plasma etch or other suitable technique is used to remove the photoresist material which serves as the spacer 176 and the spacers 177 and 178, thereby leaving the switch 110 in its final configuration, as shown in FIGURE 6.

FIGURE 8 is a diagrammatic fragmentary sectional side view similar to FIGURE 6, but showing a switch 210 which is an alternative embodiment of the switch 110 of FIGURE 6. The primary difference between the switch 210 of FIGURE 8 and the switch 110 of FIGURE 6 is that the switch 210 has a membrane 231 which is different from the membrane 131 of FIGURE 6. The remaining portions of the switch 210 are equivalent to the corresponding portions of the switch 10 of FIGURE 1 and the switch 110 of FIGURE 6, and are identified with the same reference numerals.

Membrane 231 of FIGURE 8 has ends 232 and 233 which are each fixedly supported on a respective one of the posts 17-18. Further, the membrane 231 has a central portion 236, with expansion sections 241 and 242 on opposite sides thereof. The primary difference between the membrane 231 of FIGURE 8 and the membrane 131 of FIGURE 6 is that the expansion sections 141 and 142 of the membrane 131 have a shape which is approximately a square wave or rectangle, whereas the expansion sections

241-242 of the membrane 231 each have a shape which is one period of a sine wave, from one negative peak of the sine wave to the next negative peak. The expansion sections 241-242 each project upwardly with respect to the central portion 236. The operation of the switch 210 of FIGURE 8 is generally similar to the operation of the switch 110 of FIGURE 6, and it is therefore believed to be unnecessary to provide a separate detailed explanation of how the switch 210 operates.

FIGURE 9 is a diagram which shows six diagrammatic membranes A-F, each extending between electrodes that are represented diagrammatically at 301 and 302. This is not a single switch with six membranes, but six membranes drawn from six different switches and depicted together for comparative purposes. It will be recognized that the membrane B is similar to the membrane 231 of FIGURE 8, and the membrane F is similar to the membrane 131 of FIGURE 6. The membranes D and E are variations of the membrane 31 of FIGURE 6. The membrane A in FIGURE 9 is a membrane of a preexisting type which is known in the art, and which is included in FIGURE 9 to provide a point of reference against which to evaluate the other membranes. The centers of the membranes A-F are at locations that correspond to the broken line 304.

For purposes of the discussion which follows, some exemplary dimensions will be set forth in association with the membranes of FIGURE 9, but it will be recognized that these dimensions are for illustrative purposes, and are not intended to suggest that the present invention is limited in any way to these specific dimensions. In this regard, it is assumed that the distance 306 between the electrodes 301-302 is 300 to 320 microns. Further, it is

assumed that the membranes A-F each have a thickness of 0.3 microns. It is assumed that the switches in which the membranes A-F are installed are identical except for the membranes, and that each such switch has a dielectric layer with a thickness of approximately 0.1 microns, and a spacing between the membrane and dielectric of 4 microns when the switch is deactuated.

Focusing on the membrane B, the spaced expansion sections include a single period of a sine wave at each end, which has a period 308 of approximately 15 microns, and an amplitude 309 of approximately 3 microns. The expansion sections of the membrane B are each positioned closely adjacent one of the posts 301 and 302.

Turning to the membrane C, this membrane is generally similar to the membrane B, except that the expansion section at each end includes five periods of a sine wave rather than just one period, these periods collectively adding up to a distance 313 which is approximately 100 microns. These sine waves each have the same amplitude as the waves in the membrane B, or in other words an amplitude of 3 microns.

The membranes D, E, and F are each a variation of the membrane 131 of FIGURE 6, where the ratio of the length of the expansion section to the adjacent outer portion is varied. In this regard, the outer portions of the membrane D each have a length of approximately 10 microns, and the expansion sections each have a length of approximately 90 microns. The outer portions of the membrane E each have a length of approximately 30 microns, and the expansion sections thereof each have a length of approximately 70 microns. The outer portions of membrane F each have a length of approximately 50

microns, and the expansion sections thereof each of a length of approximately 50 microns.

FIGURE 10 is a graph showing how the pull-in voltage needed for switch actuation will vary as the number of waves in the expansion sections of the membrane is varied. In this regard, point 320 represents the membrane A of FIGURE 9, which has no expansion sections or waves. Point 321 represents the membrane B of FIGURE 9, which has one sine wave in each expansion section. Points 322-324 represent variations of the membrane B, which are not separately illustrated in FIGURE 9, and which respectively have two, three and four sine waves in each expansion section. Point 325 in FIGURE 10 represents the membrane C of FIGURE 9, which has five sine waves in each expansion section.

Based on a comparison of points 320 and 321, it will be noted that providing spaced expansion sections with one sine wave effects a substantial reduction of about 70% in the pull-in voltage needed to actuate the switch. With reference to points 322-325, adding additional sine waves to the expansion sections provides still better performance, but with a diminishing marginal effect.

FIGURE 11 is a further graph corresponding specifically to the membrane B of FIGURE 9, and showing how the pull-in voltage varies in response to variation of the wavelength or period, or in other words variation of the distance 308 in FIGURE 9. It will be noted that there is a significant decrease in the pull-in voltage when the wavelength is less than about 10 times the amplitude, but limited additional benefit as the wavelength is increased beyond 10 times the amplitude.

FIGURE 12 is a graph which also corresponds to the membrane B of FIGURE 9, and shows how the required pull-in voltage varies as the amplitude 309 is varied. It will be noted that the pull-in voltage is significantly reduced as the amplitude is increased until the amplitude is approximately 20% to 25% of the wavelength or period 308. Additional increases in the amplitude provide limited additional benefit.

FIGURE 13 is a graph showing six curves, each of which corresponds to a respective one of the membranes A-F of FIGURE 9. In effect, these curves each show the extent to which the associated membrane would tend to droop in response to variations in temperature. It will be noted that, at higher temperatures, the membranes D-F tend to experience less droop than the membranes A-C.

FIGUREs 14 and 15 are related graphs which each show six curves corresponding respectively to the six membranes A-F of FIGURE 9, FIGURE 15 being a view of the lower portion FIGURE 14 with an enlarged vertical scale. The graphs of FIGUREs 14 and 15 each show how the pull-in voltage needed for actuation will tend to vary over temperature. It will be noted that the membranes C-F can be actuated throughout the indicated temperature range by a pull-in voltage which is significantly less than that required for either of the membranes A and B.

FIGURE 16 is a graph showing six lines that each correspond to a respective one of the six membranes A-F in FIGURE 9. FIGURE 16 shows the stress which occurs within each membrane at different temperatures, when the membrane is in its deactuated position. It will be noted that the membranes C-F all experience substantially less stress than the membranes A and B.

FIGURE 17 is a graph showing six lines which each correspond to a respective one of the six membranes A-F of FIGURE 9. FIGURE 17 shows how the tensile stress within each membrane varies with temperature when the membrane is in its actuated position, or in other words its flexed position. It will be noted that the most stress occurs at low temperatures, that the membrane C experiences substantially less internal stress at low temperatures than the membranes D-F, and that all of the membranes C-F experience less stress than either of the membranes A and B.

FIGUREs 18 and 19 are similar diagrammatic views showing the left half of the membrane F of FIGURE 9, at selected temperatures. FIGUREs 18 and 19 are each based on the assumption that the membrane is fabricated in a manner so that it has no thermal deformation at a temperature of 80°C. FIGURE 18 shows the nature of the deformation that the membrane will experience as it is heated from 80°C to 100°C. FIGURE 19 shows the deformation which the membrane will experience as it is cooled from 80°C to -40°C. It will be noted from the right side of FIGURE 19 that the central portion of the membrane does not experience substantial deformation or move upwardly or downwardly as the ambient temperature is varied across the 120°C temperature range from -40°C to 80°C. In contrast, it will be noted from the right side of FIGURE 18 that the central portion of the membrane experiences some deformation and moves downwardly a small distance when the membrane has been heated to 100 C.

In effect, FIGUREs 18 and 19 are showing the manner in which the membrane will tend to be deformed as a result of the different coefficients of thermal expansion

(CTE) of the membrane and the associated substrate. Tilting of the vertical portions of the membrane provide compensation across the 120°C temperature range for the CTE mismatch between the membrane and the substrate, while avoiding deformation of the central portion of the membrane.

The present invention provides a number of technical advantages. One such technical advantage results from the provision in a membrane of resilient structure such as spaced expansion sections that are capable of yieldably expanding in a direction lengthwise of the membrane, so as to increase an effective length of the membrane and thereby facilitate resilient flexing of the membrane between positions corresponding to actuated and unactuated states of a switch. This reduces the pull-in voltage needed to actuate the switch.

A further technical advantage results from configuration of the expansion sections to include first and second portions that are approximately vertical and parallel, and a third portion which extends between the first and second portions approximately perpendicular thereto. The first and second portions can tilt to some extent so as to facilitate either expansion or contraction of the effective length of the membrane, in order to compensate for a mismatch in the CTEs of the membrane and the substrate. By compensating for the CTE mismatch, a reduction is realized in the extent to which the pull-in voltage varies over temperature. The switch can thus operate over a wider temperature range with a lower pull-in voltage than existing switches.

In one form of the present invention, the expansion sections project downwardly toward the base section

relative to the rest of the membrane. As a result, these expansion sections engage the base section before the central portion of the membrane engages the dielectric layer over the electrode. The central portion then flexes until it engages the dielectric layer. One advantage of this approach is that, whenever the DC bias voltage is terminated to effect deactuation of the switch, a significant upward force is exerted on the central portion of the membrane so as to initiate its movement away from the dielectric layer and electrode. This significantly decreases the likelihood that residual charge in the dielectric layer will create an electrostatic attraction which can maintain the membrane in its actuated position even after the DC bias voltage has been turned off. A related advantage with this arrangement is that the increased restoring force is achieved without requiring an increased pull-in voltage to move the membrane from its deactuated position to its actuated position.

Still another advantage is that the provision of expansion sections permits the membrane to be somewhat thicker than would be the case with a pre-existing membrane having no expansion sections. The thicker membrane lowers the effective resistance of the membrane, which in turn permits the switch to operate at a higher power level.

Although several embodiments have been illustrated and described in detail, it will be understood that various substitutions and alterations are possible without departing from the spirit and scope of the present invention, as defined by the following claims.